Numerical simulations of supersonic film cooling for liquid rocket nozzle applications: A validation study

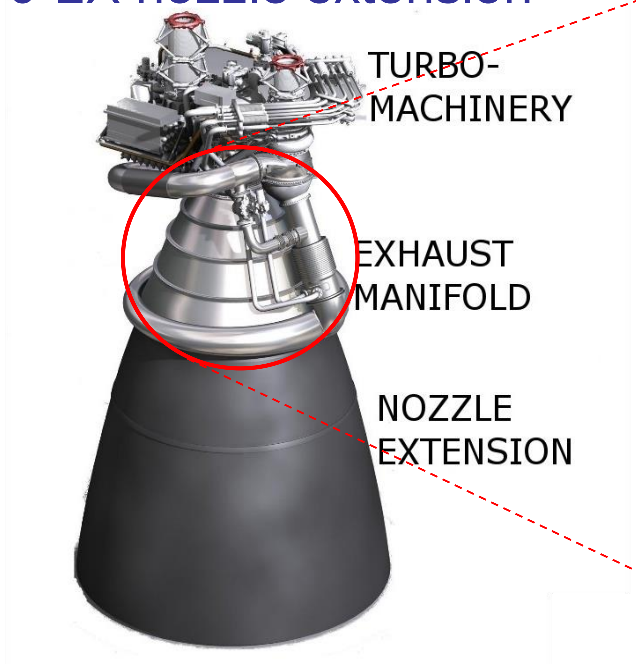
Salman Verma, Chandan Kittur, Colin Adamson, Arnaud Trouve & Christopher Cadou
University of Maryland, College Park

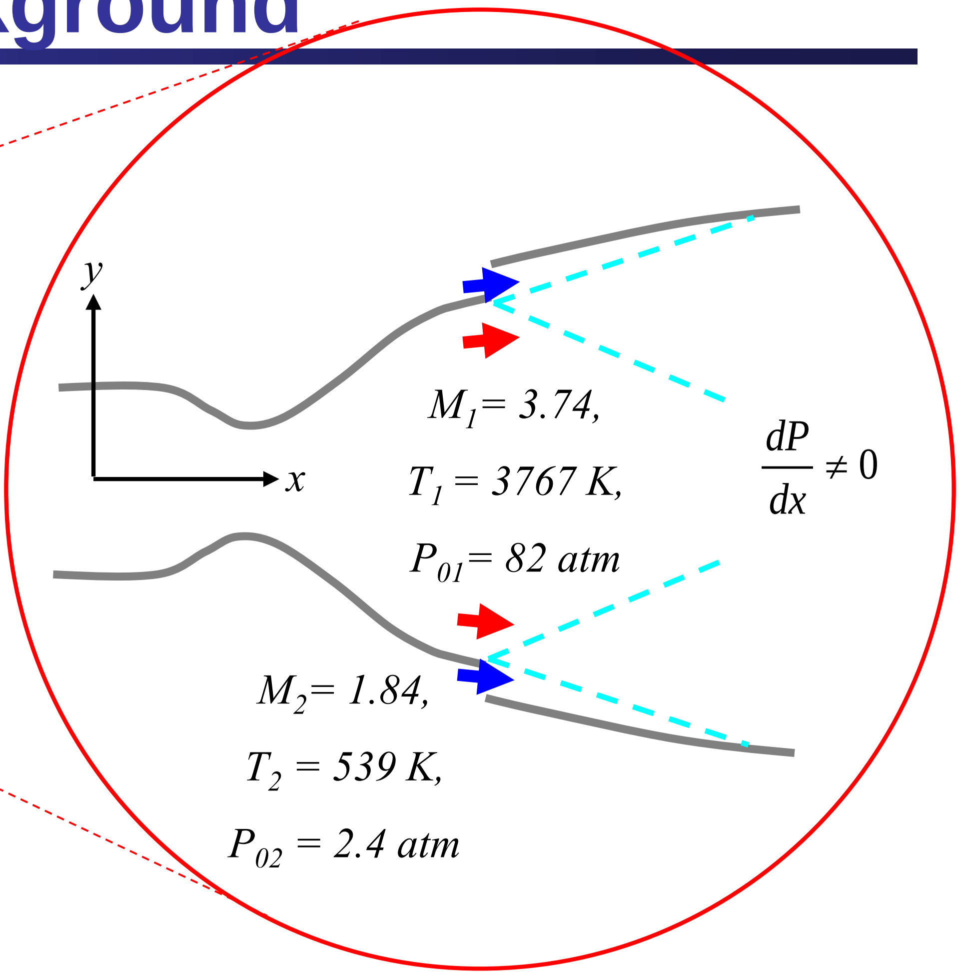
Joseph Ruf
NASA MSFC

Introduction

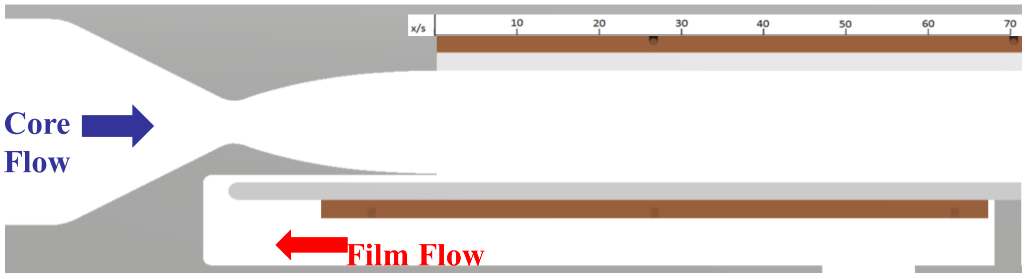
Background

- J-2X nozzle extension





- UMD tunnel
  - J-2X relevant conditions
    - Core Ma=2.4
    - Film Ma
      - 0, 0.5, 0.7 & 1.2



Motivation

- **Some previous studies** - Weighardt (ZWB, 1900,1946), Lucas et al. (NASA, TN D-1988, 1963), Goldstein (Advances in Heat Transfer, 1971), Aupoix et al. (AIAA, 36, 1998) & Konopka et al. (AIAA 2010-6792)

- More experimental data is needed to adequately validate CFD codes for supersonic film cooling
  - E.g., most studies do not provide flow profiles, with no study providing minimally-intrusive flow profiles

- **RANS and LES techniques should be further tested to assess performance for film cooling flows**

Objective

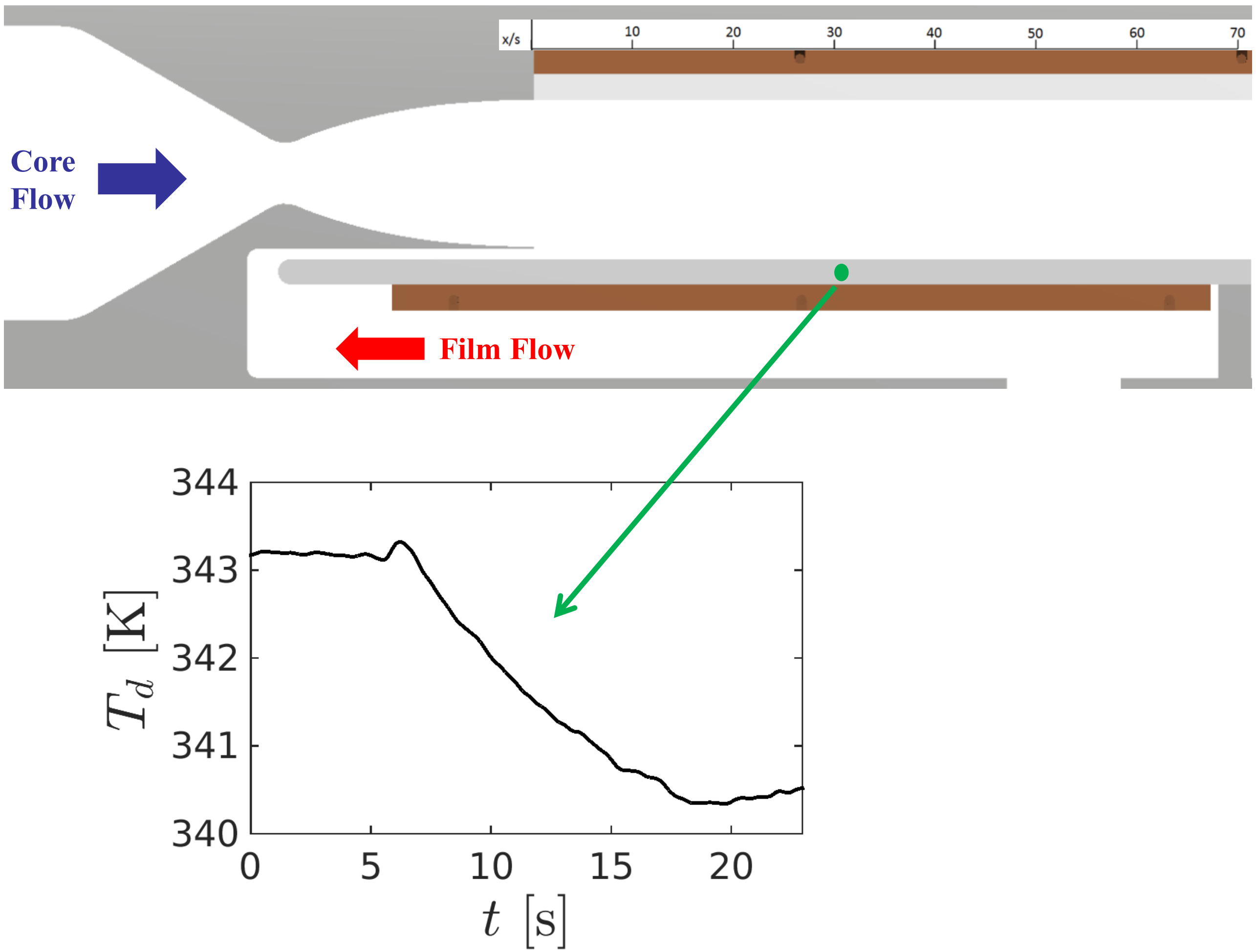
- Develop a detailed understanding of film cooling fluid dynamics so that predictive CFD approaches can be developed
  - Generate a database of measurements in ‘J-2X’ relevant **model problems*** that can be used for CFD validation
  - **Thorough assessment of RANS (using Loci-CHEM) and LES (using OpenFOAM)**

*****Model problems**

- **Film cooling over a flat plate at constant pressure**
- Film cooling over a flat plate with a pressure gradient

Experimental heat flux

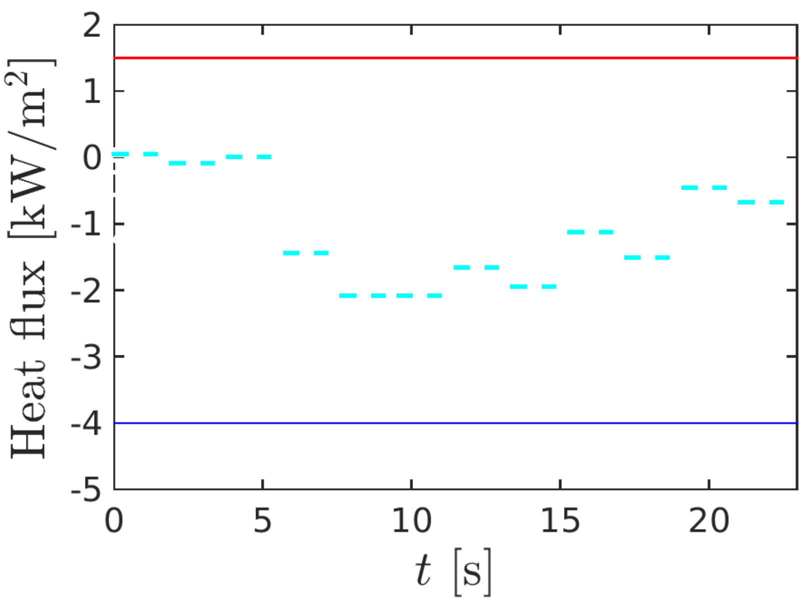
Inverse modeling

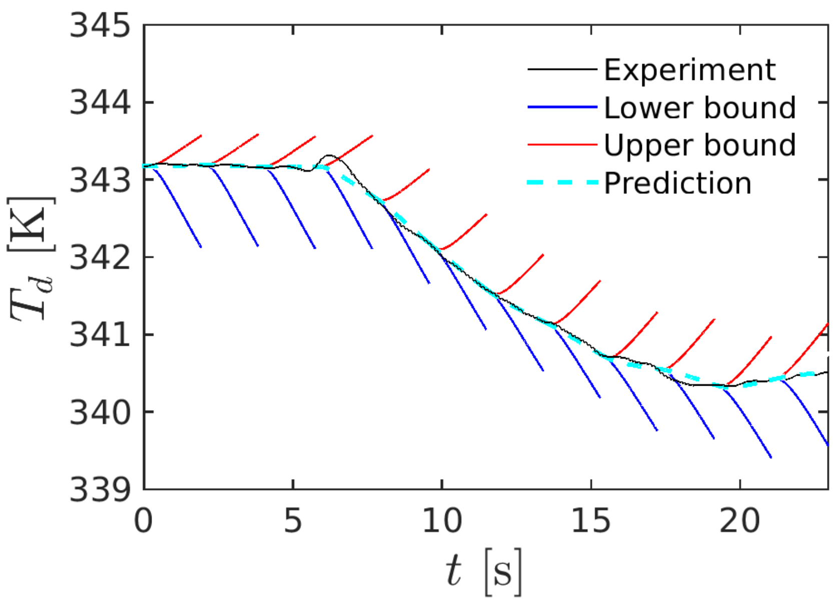


- **Inverse modeling** - measure temperature inside the solid and reconstruct unknown wall heat flux

Heat flux determination procedure

- Divide the measured temperature data into several sections
- Tune heat flux at the surface for reproducing the measured temperature inside the solid
  - Done using the **bisection method** with a **1D finite difference based conduction solver**

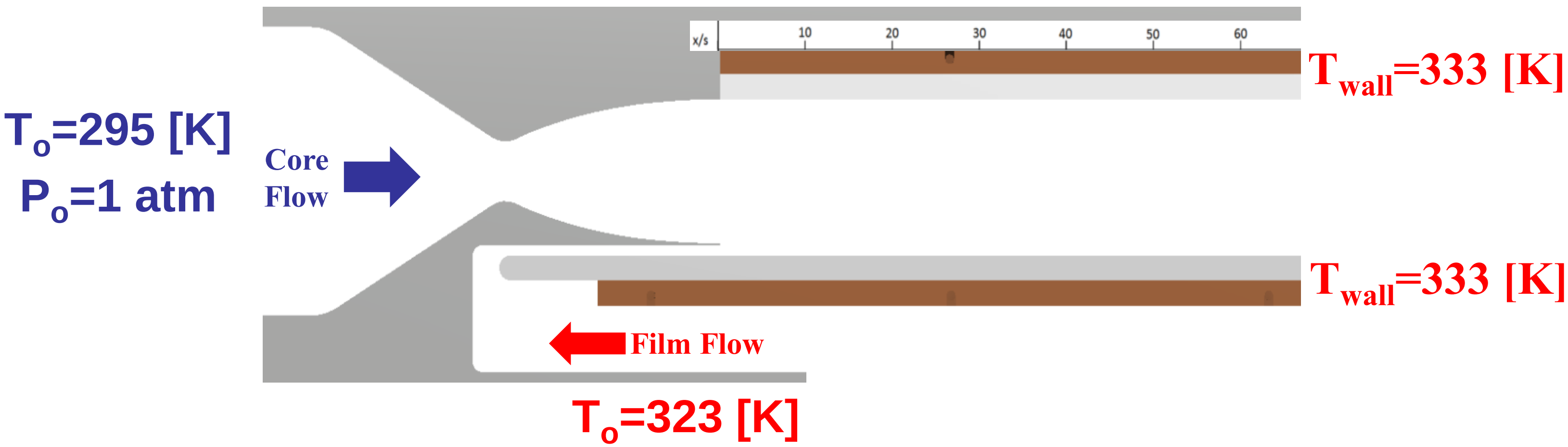


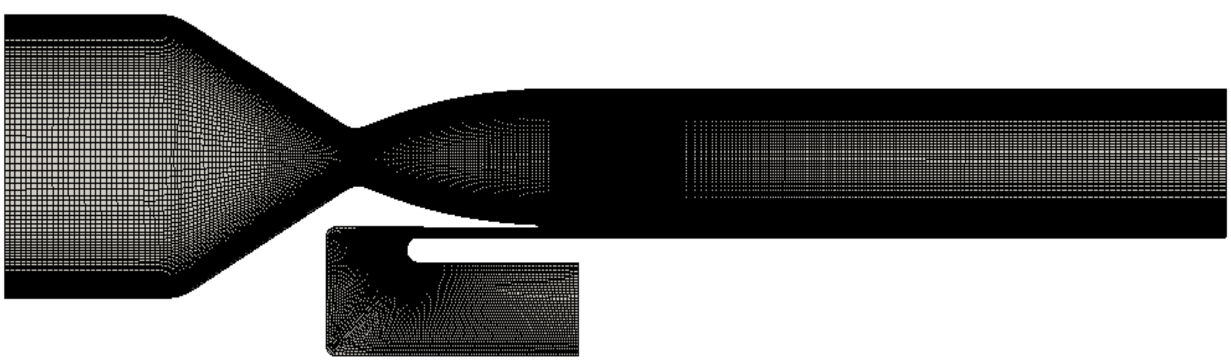


Reynolds Averaged Navier Stokes (RANS) simulations:

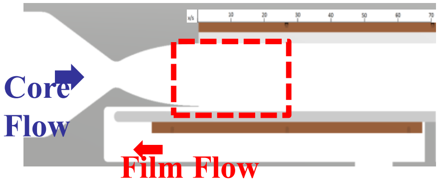
Loci-CHEM

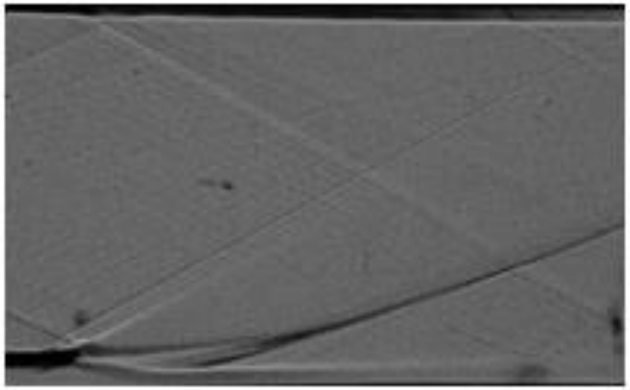
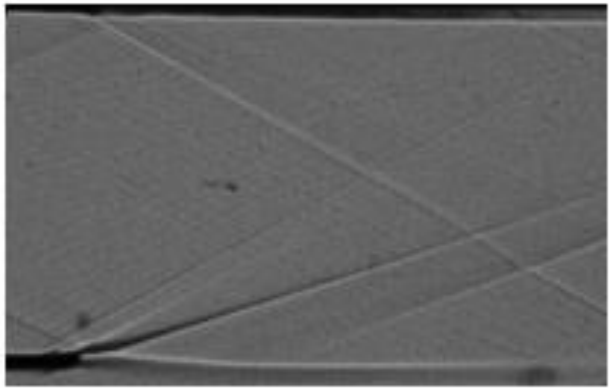
RANS: boundary conditions & mesh

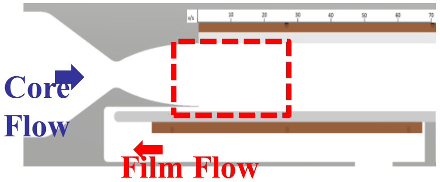


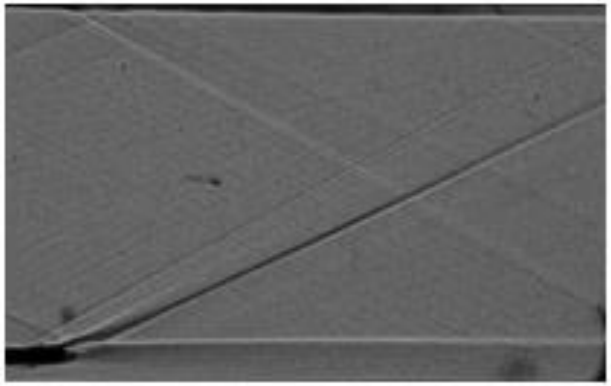
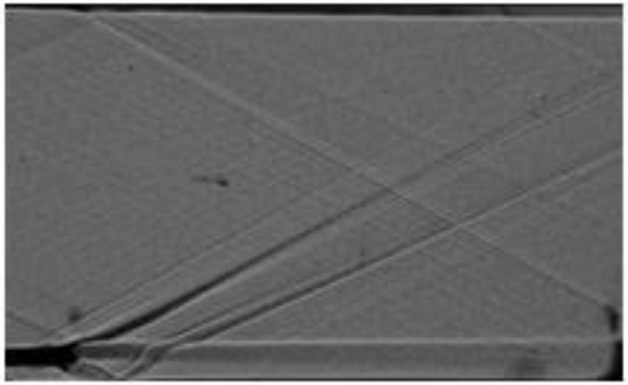


RANS vs experiments: schlieren

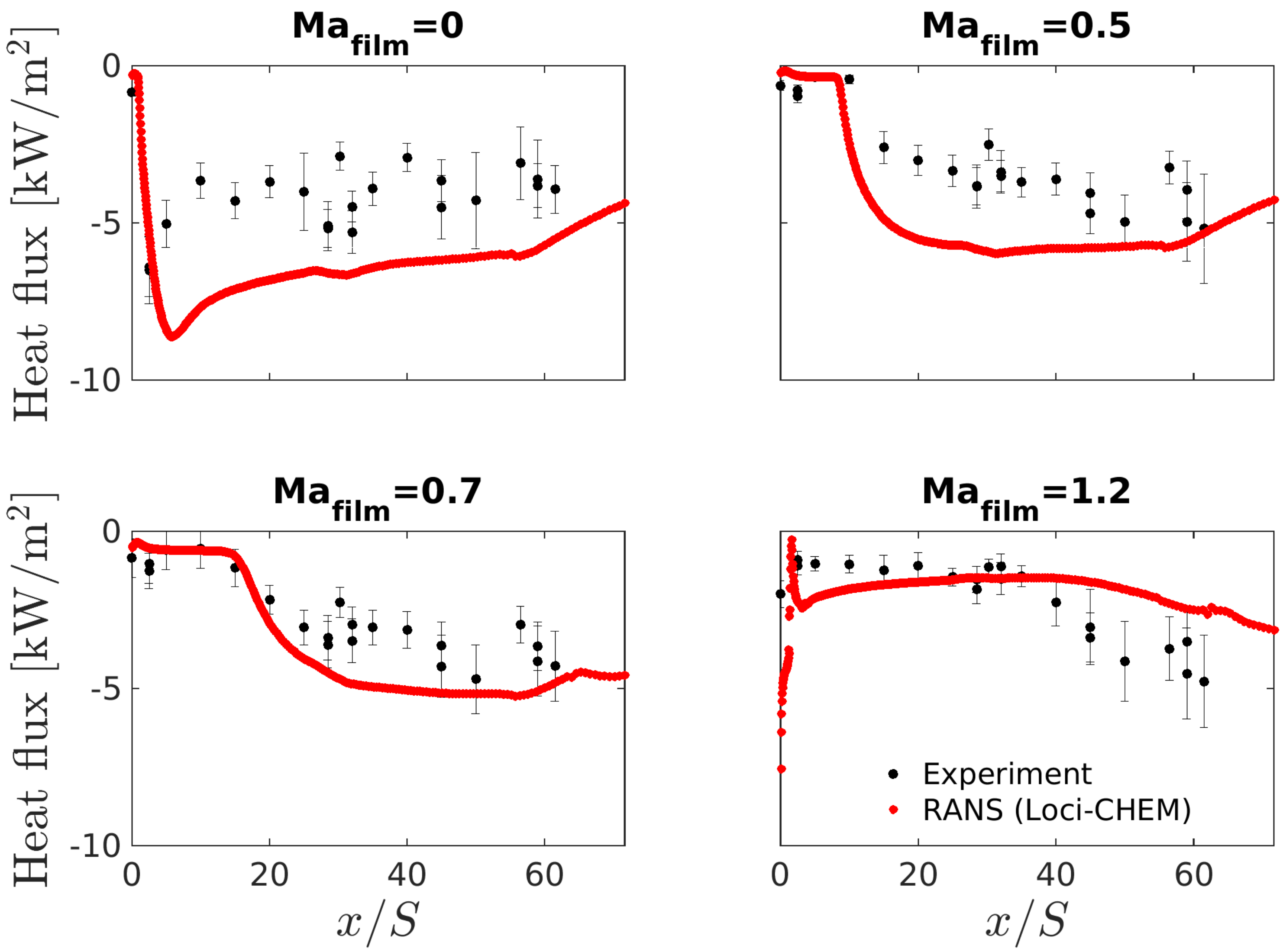


	Experiments	RANS
$Ma_{film} = 0$		
$Ma_{film} = 0.5$		

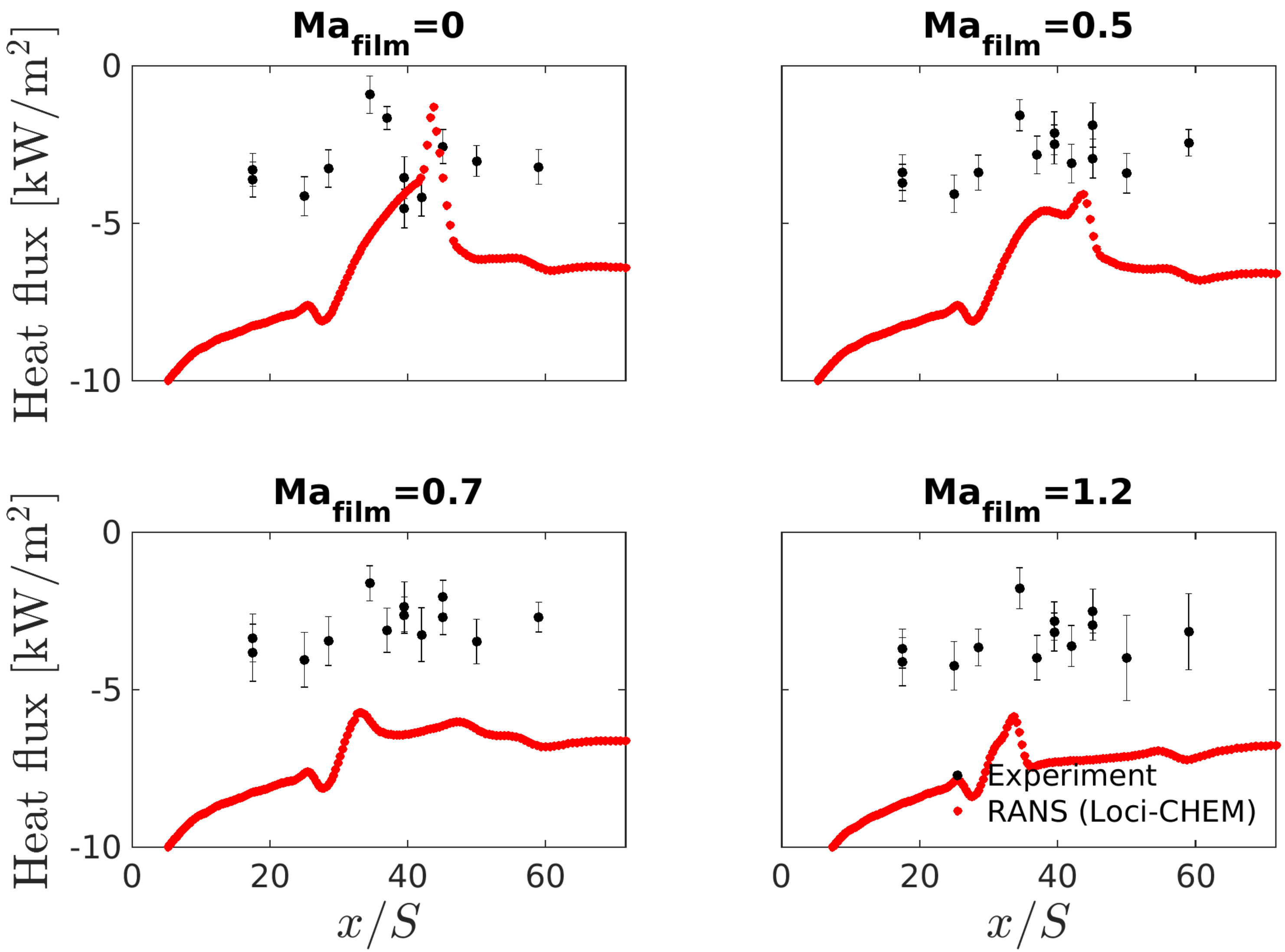


	Experiments	RANS
Ma_{film} = 0.7		
Ma_{film}=1.2		

RANS vs experiments: lower wall heat flux

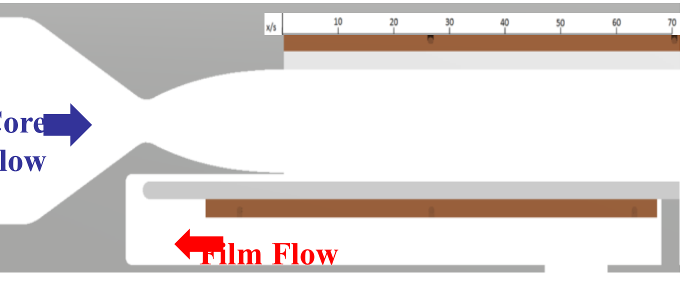


RANS vs experiments: upper wall heat flux

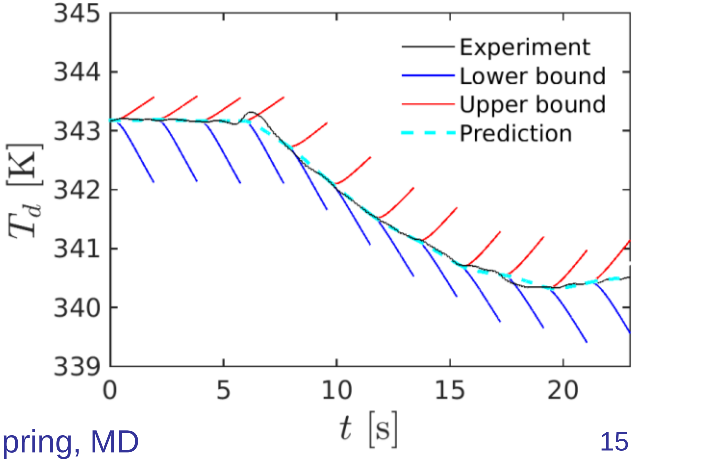


Discrepancies - why?

- Possible reasons and solutions
  - Limitations of **RANS models** e.g., difficulty in handling variable density flows
    - LES
  - **Fixed temperature BC** for heated walls
    - Conjugate Heat Transfer (CHT)



  - Relatively new **inverse modeling code**
    - Check effects of different parameters
  - **Experiments**
    - Understand the instrumentation better

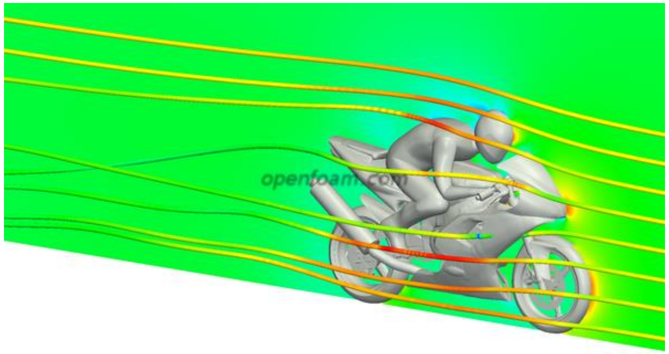


Large Eddy Simulations (LES): OpenFOAM

Why OpenFOAM?

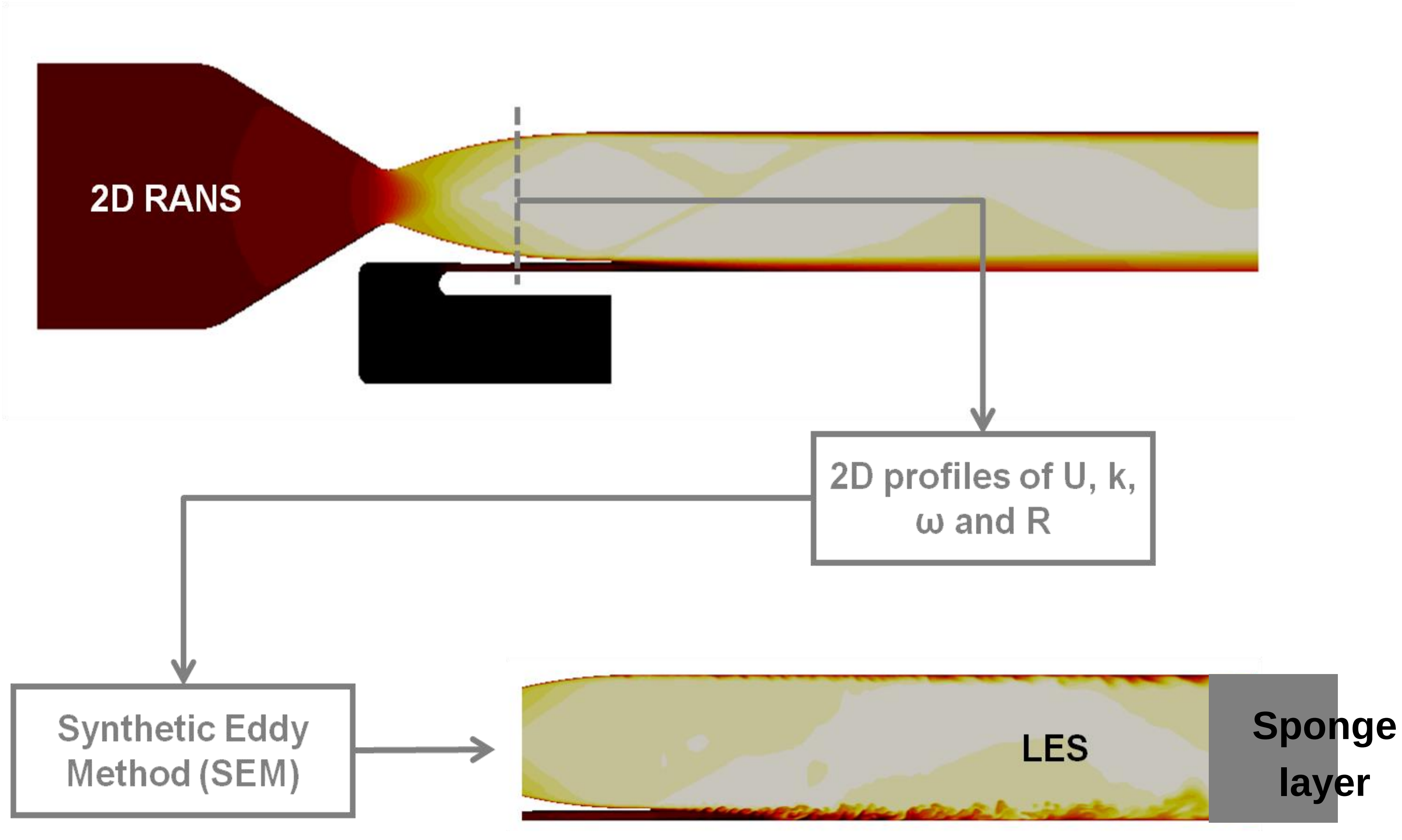
- Getting very popular in
  - Academia &
  - Industry

http://openfoam.com/

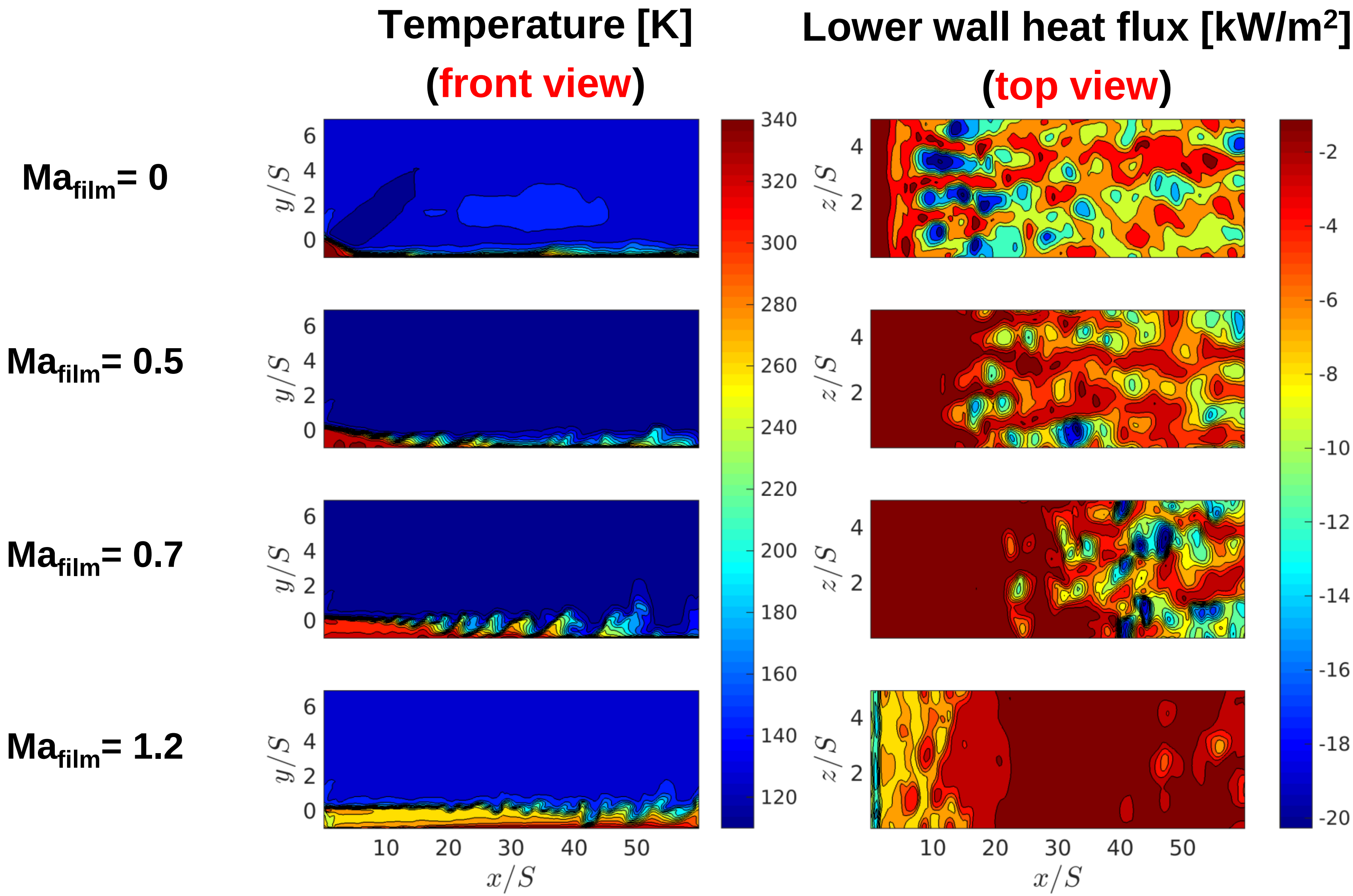


- Why?
  - Free
  - Open source
  - Easy to extend/develop
  - Several models for e.g., turbulence, combustion
  - Unstructured meshes
  - Scalability up to 1000s of CPUs

LES: inflow schematic & sponge layer

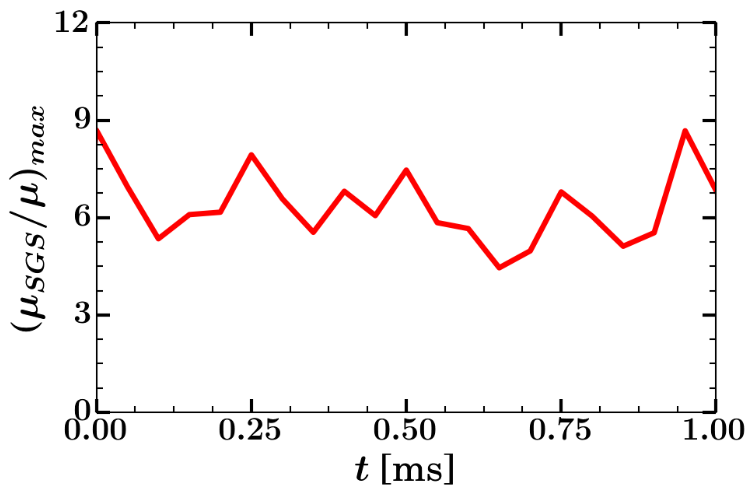


Coarse LES: wall heat flux contours

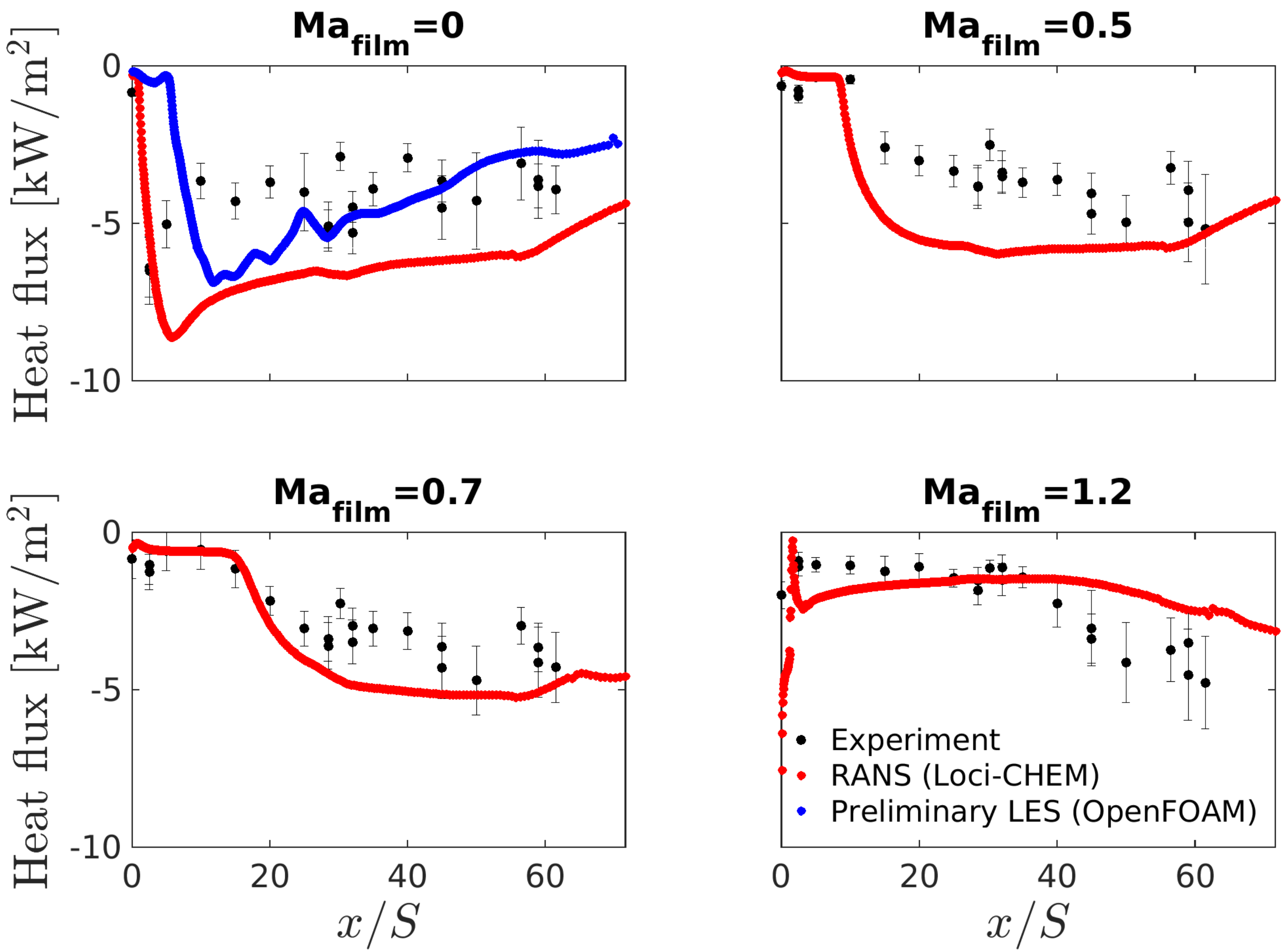


LES: domain size & resolution

cell count (million)	L_{span} (in S)	Δx^+	Δy^+	Δz^+
13	2.2	30	2.5-20	25



LES vs experiments: lower wall heat flux



Concluding remarks

- RANS (Loci-CHEM)
  - Flow structures in reasonable agreement with experimental data
  - Comparison with experimental heat flux profiles not impressive
    - Disagreement worse on the upper wall

- LES (OpenFOAM)
  - Providing high resolution insight into the film cooling dynamics
  - Preliminary LES shows improvement over RANS
  - Higher resolution simulations expected to provide more accurate results

Future work

- Heat flux determination (or inverse modeling) procedure
  - Check sensitivity to different parameters e.g., number of divisions
- Reynolds Averaged Navier Stokes (RANS) simulations
  - Understand the source of discrepancies in heat flux profiles
  - Conjugate heat transfer
- Large Eddy Simulations (LES)
  - Conduct higher resolution simulations
  - Larger span size
  - Resolve the upper wall

Acknowledgements

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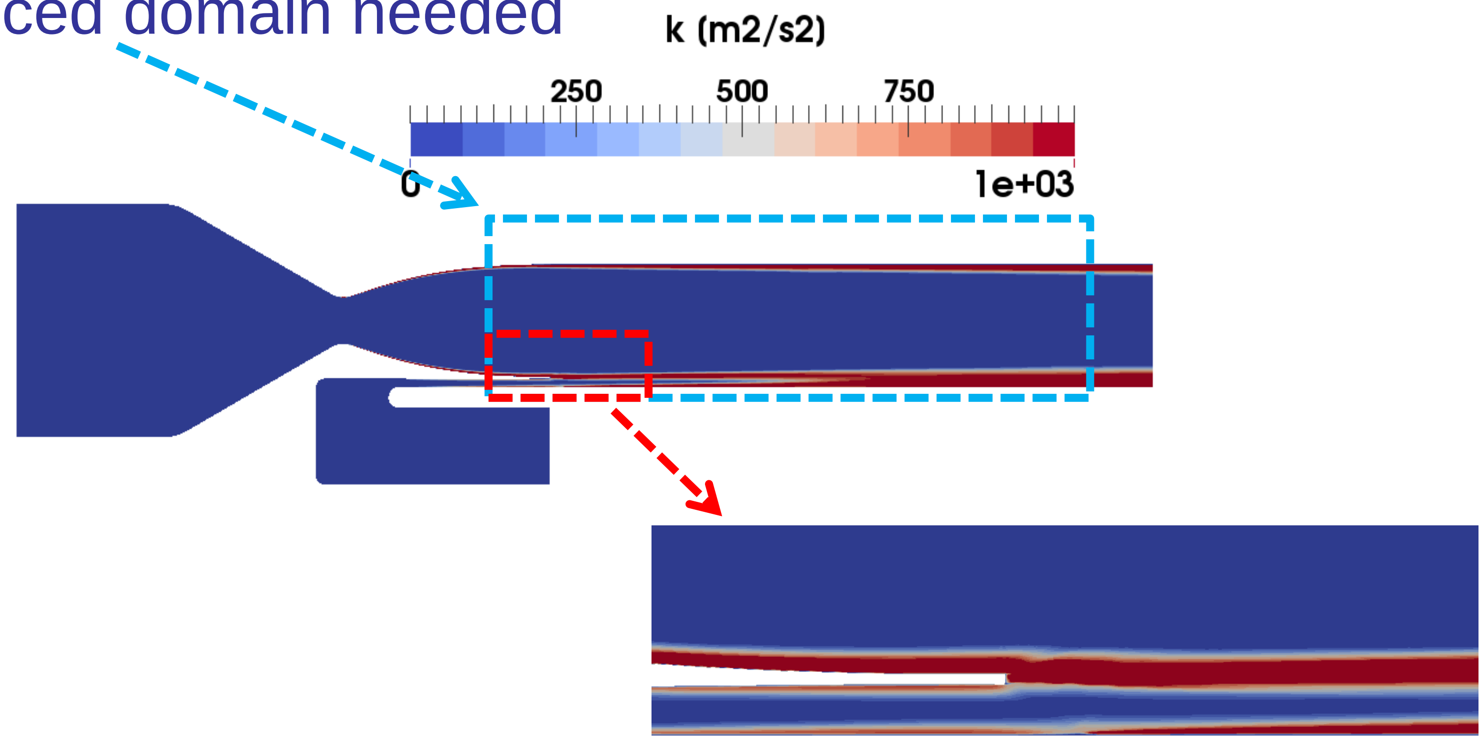
Thank you; questions?

Back up slides

LES: domain

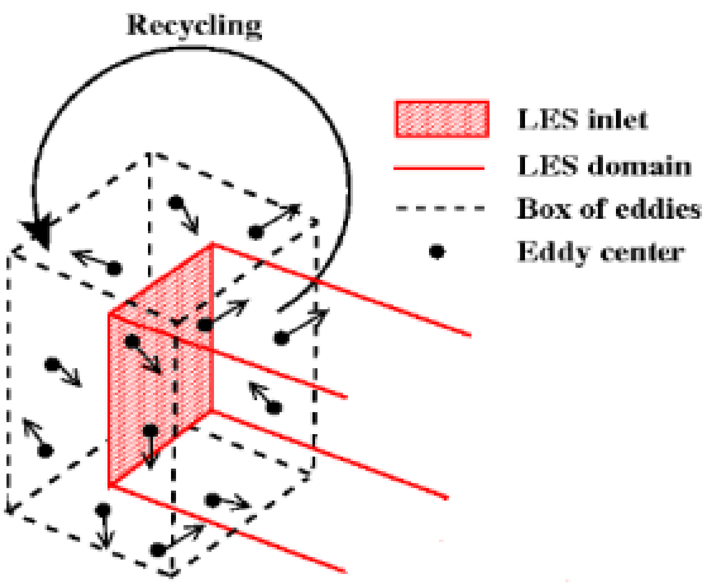
- Can not do LES of the full domain (high computational cost)
- Reduced domain needed



- But inflow fluctuations become important with reduced domain due to relatively high turbulent kinetic energy

LES: inflow (Synthetic Eddy Method)

- Jarrin et al. (IJHFF, 27, 2006)
- Velocity signal – sum of synthetic eddies with random position & intensity
- Eddies convected in a virtual streamwise periodic domain around the inlet boundary
- Synthetic eddy characteristics determined e.g., from a RANS solution

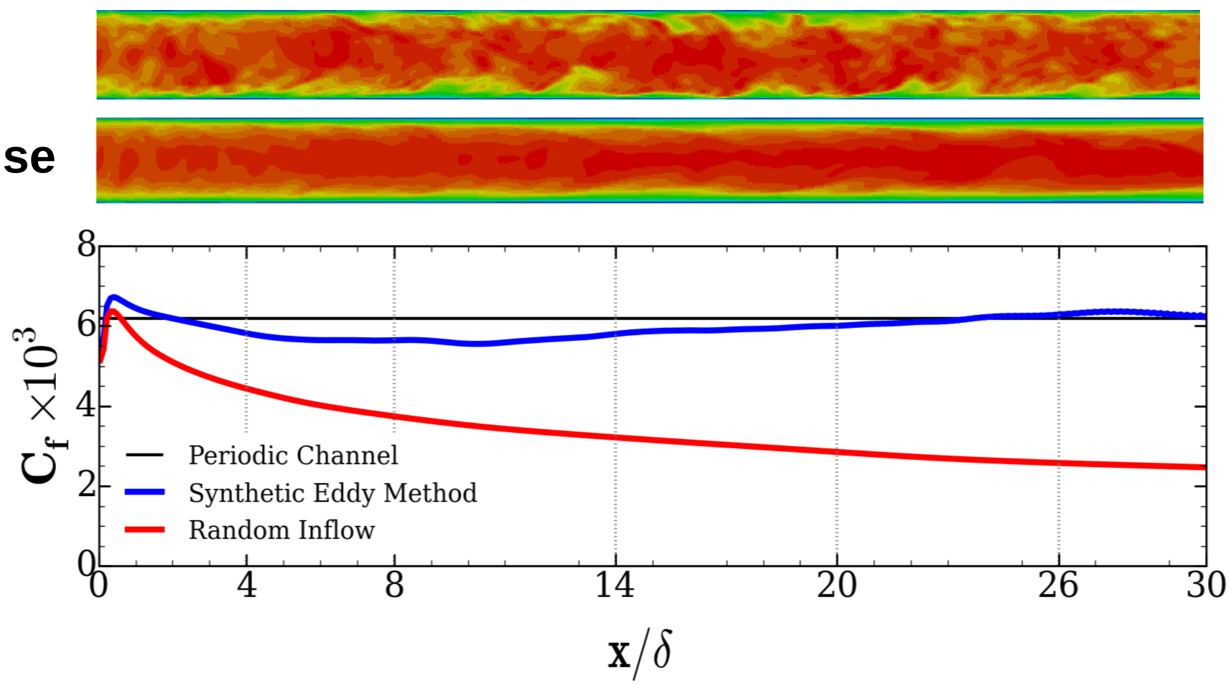


LES: inflow validation

- Synthetic Eddy Method (**SEM**)
  - — Inlet signal evolves into a natural turbulent signal in roughly 15 x/δ
- Random noise at the inlet
  - — Inflow signal is damped by the solver and flow re-laminarizes
- Consistent with Jarrin et al. (IJHFF, 27, 2006)

SEM

Random noise



LES: sponge layer

- To avoid reflections from the outlet a **sponge layer (grey)** was used

- Flow fluctuations are damped in the sponge layer by source terms before it leaves the domain

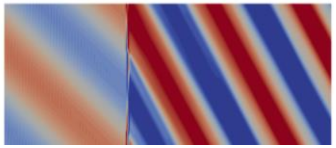
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = \sigma(\rho_{\mathrm{ref}} - \rho),$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j + p\delta_{ij} - \tau_{ij}) = \sigma[(\rho u_i)_{\mathrm{ref}} - \rho u_i],$$

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x_j}[(E+p)u_j + q_j - u_k\tau_{kj}] = \sigma(E_{\mathrm{ref}} - E),$$

Damping/source terms

- Tested on the shock-vorticity/entropy wave interaction problem from Johnsen et al. (JCP, 229, 2010)



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